Design and implementation of a pattern tracking system with visual control based on images for an UAV in indoor environments

Arroyo Paredes Margarita Gioconda, Cordonez Acosta Elvis Gustavo

Departamento de Eléctrica y Electrónica

Carrera de Ingeniería en Electrónica e Instrumentación

Artículo académico, previo a la obtención del título de Ingeniera en Electrónica e Instrumentación

Msc. Pérez Gutiérrez Milton Fabricio

23 de Julio del 2020

2020 6th International Conference on Mechatronics and Robotics Engineering

Design and Implementation of a Pattern Tracking System with Visual Control Based on Images for an UAV in Indoor Environments

Elvis Cordonez-Acosta, Margarita Arroyo-Paredes, Milton Pérez-Gutierrez, David Rivas-Lalaleo
Universidad de las Fuerzas Armadas ESPE
Carrera de Ingeniería en Electrónica e Instrumentación
Sangolquí, Ecuador
e-mail: {egcordonez, mgarroyo2, mfperez3, drrivas}@espe.edu.ec

***Abstract*—For target tracking when UAV's operate in indoor environments, they present difficulties when using the GPS signal. One of the solutions to this type of problem is visual feedback through a camera on board the aircraft. In this work we developed two types of controllers a classic PID and a controller that uses the kinematic model of the UAV that allows to make the tracking of a defined pattern in space within indoor environments, both controllers receive a visual feedback through a camera on board the UAV that by means of a calibration estimates the distances of the UAV with respect to the pattern in each of its axes, finally a comparison of results is made and it is determined that the controller with kinematic model presents an error less than 5% for each axis in trajectories greater than one meter being the most optimal in this work.**

Keywords-UAV; controllers; visual; image; position; PID; kinematic

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are aircraft capable of autonomously maintaining a stable and controlled flight level. These aircraft have different configurations and design characteristics such as size, weight, among others, the UAV's have sensors, controllers and communication equipment to establish their course and trajectory. Currently, they have been equipped with specialized equipment that allows them to perform tasks in the forestry, agricultural, civil engineering, and architectural areas, among others. It is worth noting that one area where they have had the greatest impact in recent years is in security and defense, where projects have been developed for intruder detection, tracking of targets and people, among others [1].

The most common disadvantages that occur during the flight of a UAV are: impacts with obstacles, crashes due to loss of communication, destabilization by wind gusts, this occurs mainly because of being in unstructured environments; on the other hand, there is the loss of trajectory due to communication failures with the Global Positioning System (GPS), etc. In order to mitigate these problems, UAV's are equipped with sensors that manage the positioning of the aircraft in space, among the most well-known are laser sensors, altimeters and high sensitivity GPS receivers. In small range platforms the implementation of this type of sensors is restricted by its volume and weight leaving this equipment with a limited capacity of an autonomous flight, the main application of these drones are the flights in internal or closed spaces, in this environment the GPS presents problems of multiple reception of the same signal, attenuations, among others [2].

An alternative to perform an autonomous flight is the visual feedback control or visual servoing of robotic systems that consists in the fusion of kinematics, dynamics and computer vision of the robot to control its movement efficiently [3]. This control is classified in two groups, Position Based Control (PBVS) and Image Based Control (IBVS) [4]. The IBVS with camera mounted on the UAV is implemented with a closed loop algorithm that controls the position and orientation of the aircraft and the position of the target, thus being a real time computer vision system, to land the UAV in a known landing point, through corner detection and the corresponding match [5]. There is also the use of advanced controls [6], in which the implementation of a fuzzy logic control achieves object tracking, route tracking and obstacle avoidance, obtaining results with great efficiency in the control, detecting fixed and mobile objects, providing a very useful tool when it is required to detect objects with established and defined characteristics [7-8]. The tracking of objects by means of a pan-tilt camera achieves the position and orientation with the least possible error, and the use of backward techniques makes the controller respond with a uniform tracking [9]. Other algorithms based on detection and monocular processing that detect the obstacles according to the physical size where they are located allow to determine what is the probability of an approach or impact, so that the controller implemented in the computer executes a control action to the UAV to avoid contact with the obstacle [10-14].

The use of this technology has allowed the implementation of positioning controllers by means of cameras as a feedback element, as in the work developed at Lin that requires precise image segmentation so that the UAV can follow an object or a master image in a disordered environment. To solve this problem, the method of corner detection and comparison of rectangular templates is used, in which a fixed threshold is used to compare a target image with a previously stored template as in the work developed by Nex [15] and Pestana [16]. The squaring of points through the camera mounted in the UAV allows the control

978-1-7281-5739-9/20/$31.00 ©2020 IEEE

system to consider the current position of the object, based on this the system has the coordinates of the object in movement, allowing to follow it and keep it in the reference points in a new coordinate, the same that based on the decisions of the controller is the one that executes the control actions and it is possible to reach the reference in the shortest time. [17-19].

In the present work a position control based on images is developed, in which the characteristics of a defined pattern captured by the already incorporated camera of a UAV are selected and tracked, which are transformed into spatial positions that serve as feedback from two controllers, a classic PID and inverse Jacobian that is based on the kinematic model of the platform, These in turn determine the appropriate speeds that are sent to the aircraft engines allowing it to move in its three axes compensating for the displacement of the UAV with respect to the movement of the pattern to finally position itself in front of the target operating indoors. The results obtained are statistically analyzed in order to obtain a response with an error between a range of ±5 % for linear trajectories higher than 1 meter in the different axes of movement of both controllers verifying the effectiveness of each of them.

This article is divided in the first section consists of the introduction, the second the development of the controllers, the third the experimentation, the fourth the presentation of the results, the fifth the conclusions and ending with the future work.

II. PROCEDURE

The development of the controller covers the following stages: (a) calibration of the on-board camera of the aircraft, (b) development of the classical PID controller and (c) development of the controller by the reverse Jacobin. Figure 1 shows the composition of the system.

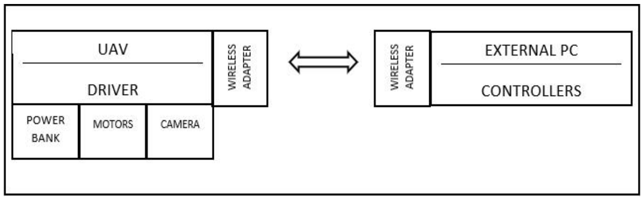


Figure 1. General schema of the system.

The movement of the UAV takes into account the mobile reference system of the UAV, which will have no relation to the fixed reference $\sum 0$ that represents the Earth's surface. Figure 2 shows how the UAV performs an image-based tracking control by positioning itself against the reference pattern when it moves in space.

To verify this proposal, an unmanned aerial vehicle of the DJ-Tello series is used, which among its features implements an open communication library compatible with Python, the image feedback is done in OpenCV and the pattern to be identified will be an Aruco binary marker that is defined as a synthetic square composed of a black border and an internal binary matrix that determines its identifier (id). As shown in Figure 3.

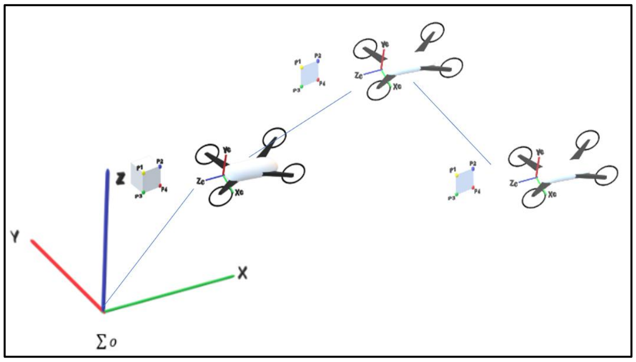


Figure 2. Space trajectories described by the UAV when tracking the pattern.

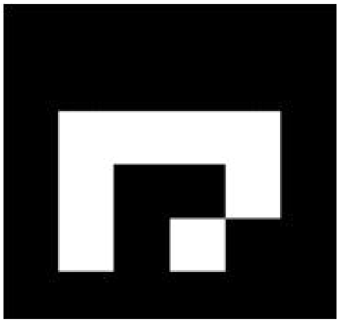


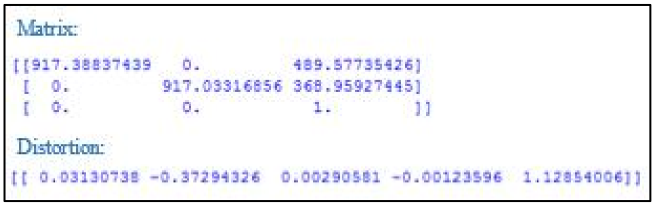
Figure 3. Pattern provided by the Aruco bookstore, necessary for the rotation and objective translation matrices of the UAV.

A. Calibration

This process consists of obtaining the intrinsic and extrinsic values of the camera to position the pattern in the center of the focus frame, for this purpose a 10x7 frame binary calibration image is used, the dimensions of each frame are 30x30mm this image is photographed at different angles as shown in figure 4. The parameters obtained are shown in Figure 5 with which the centering of the image was obtained as shown in Figure 6.

Figure 4. Photographs taken with the dron dj Tello to obtain the intrinsic and extrinsic parameters of the camera.

Then, the system adjusts the rotation matrix that corresponds to the rotation angles in each axis known as yaw, pitch and roll and the translation matrix that takes care of the displacements in the X, Y, Z axes. The result of its correct operation can be seen in figure 7 where panel a) is a shot from a camera external to the system and shows how the UAV is 500 mm from the pattern and panel b) shows the axes drawn in the pattern as seen from the aerial platform camera.



```
Matrix:
[[917.38837439   0.         489.57735426]
 [  0.         917.03316856 368.95927445]
 [  0.           0.           1.        ]]
Distortion:
[[ 0.03130738 -0.37294326  0.00290581 -0.00123596  1.12854006]]
```

Figure 5. Parameters of the dron djTello camera after calibration.

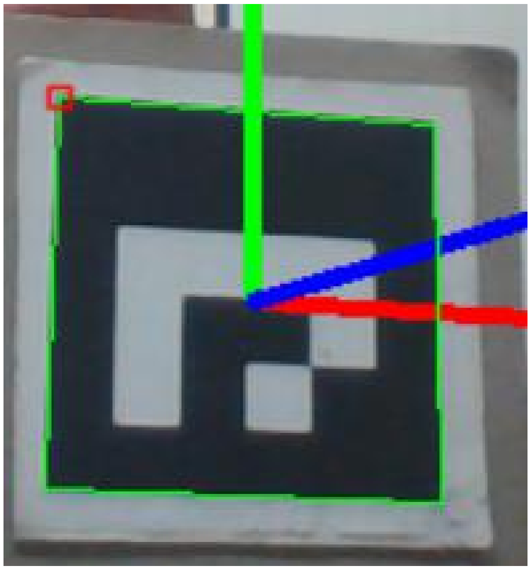


Figure 6. Position axes drawn on the aruco-maker (Red X-axis, Green Y-axis, Blue Z-axis).

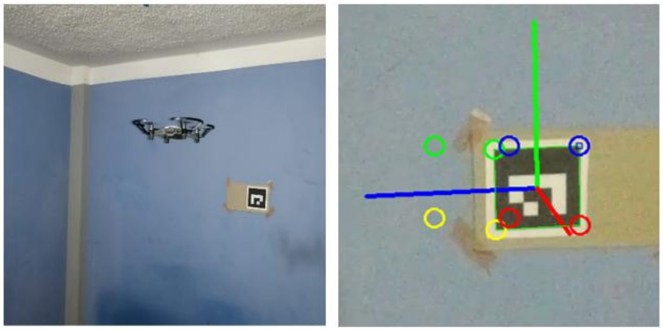
B. *Development of the Classic PID Controller*

A Derivative Integral Proportional Control (PID) is a control mechanism that calculates the error that exists between a sensed or measured value and a desired value, where the proportional value depends on the actual error, the integral of the previous error and the derivative a prediction of future errors.

This controller is defined by Equation 1:

$$vel(t) = K_p e(t) + K_i \int e(t)dt + K_d \dot{e}(t) \qquad (1)$$

Where K_p,K_i,K_d are the Proportional, integral and derivative constants respectively and $e(t)$ represents in this process the error that will exist in each axis.



(a) (b)

Figure 7. UAV positioned 500mm from the aruco-maker and showing the image axes.

In this case this controller will adjust the speeds in order to keep the pattern in focus. The diagram in Figure 8 explains how this process is performed.

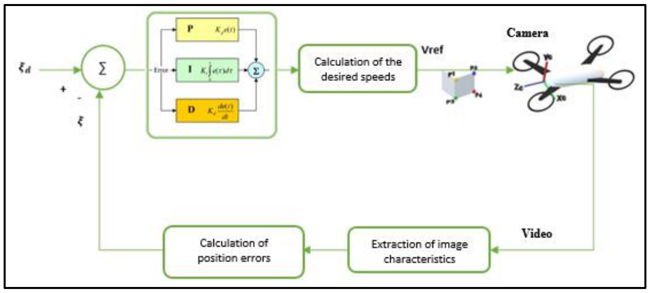


Figure 8. Position control diagram for the UAV using PID technique.

C. *Development of the Reverse Jacobian Controller*

The law of control by Jacobiana Inversa is a mechanism commonly used in platforms that require to control their position or displacement, this controller is based on the kinematic model of the system to control that takes into account the point of interest of the whole plant, in this case the point of interest is the optical center of the camera on board the UAV.

Knowing that the kinematic model of the UAV is represented by the Jacobian matrix of Equation 2:

$$J = \begin{bmatrix} \cos(\varphi) & -\sin(\varphi) & 0 & a_c \sin(\varphi) \\ \sin(\varphi) & \cos(\varphi) & 0 & a_c \cos(\varphi) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

Where φ is the angle of rotation in the UAV Y-axis in relation to the image and a_c is the distance between the optical centre of the UAV camera and the geometric centre of the UAV in millimetres.

For the calculation of control speeds it is necessary to invert the Jacobian together with the error matrix of Equation 3:

$$Error = \begin{bmatrix} E_x \\ E_y \\ E_z \\ E_r \end{bmatrix} \tag{3}$$

Where E_x ,E_y, E_z are the translation errors (X, Y, Z) and E_r the rotation error (W):

Once you have described all the matrices needed to calculate the controller speeds, you have the expression of Equation 4:

$$vel = J^{-1} * k * \tanh(Error) \tag{4}$$

Where k represents the gain matrix for each axis of motion of the UAV.

The diagram in Figure 9 below shows how the UAV works by calculating the inverse Jacobian.

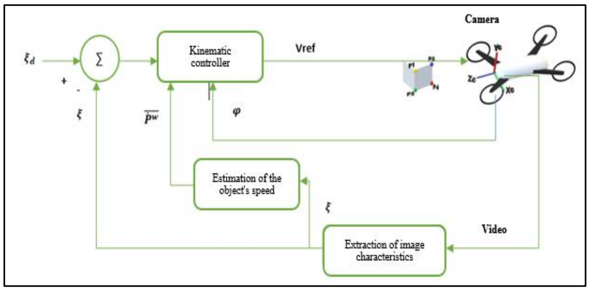


Figure 9. Position control diagram for the UAV by calculating the inverse Jacobian.

III. EXPERIMENTATION

In order to compare the behaviour of the controllers, the following experiment was carried out, which consists of moving the pattern over a path of y=x, the distance travelled will be 1 metre in 8 seconds.

A. *UAV with PID Control*

Under the conditions described in the experiment, the PID controller is tuned using the limit gain technique, where the K gain value is raised until it has an error in a stable state, which is decreased by raising the integration constant until a very small error is obtained and avoiding generating oscillations in the system. If oscillations occur in the process, these are compensated by entering a derivation constant in the controller thus obtaining the constants $Kp, Ki\ and\ Kd$ for each of the axes to be controlled which are shown in table I. When applying these constants, the response of this controller can be seen in Figure 10.

From this experiment it can be seen that the displacement in the Z axis (blue) has a pulse envelope of 10% and then it presents oscillations during all its travel, in the X axis (red) it is observed that it has a pulse envelope around 5% and similar that in the Z axis it presents oscillations during all its travel, in the Y axis (green) in spite of not existing a pulse envelope it presents more notorious oscillations from the beginning of its trajectory.

TABLE I. CLASSIC PID CONTROL TUNING CONSTANTS FOR EACH AXIS

$Axis$	kp	ki	kd
x	1,50	0,005	0
y	3,00	0,009	0
z	1,25	0,004	0
w	0,10	0,001	0

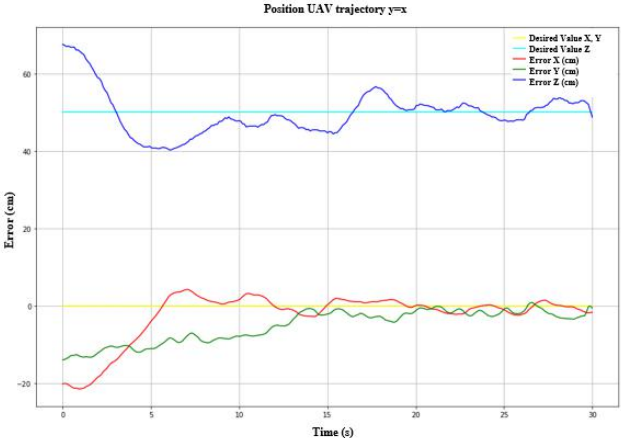


Figure 10. Errors in centimeters of the X, Y, Z axes of the UAV using the PID controller.

B. *Control by Jacobian Calculation*

For the following experiment the control is based on the Jacobian matrix described in Equation 2. From this process the constants are extracted from the gain matrix shown in Equation 5 in reference to the parameters of the experiment.

$$k = \begin{bmatrix} 0.500 & 0 & 0 & 0 \\ 0 & 1.000 & 0 & 0 \\ 0 & 0 & 1.000 & 0 \\ 0 & 0 & 0 & 0.250 \end{bmatrix} \tag{5}$$

This gain matrix is obtained from an identity matrix of the same dimensions as the Jacobian matrix of the system, by means of an adjustment of small increments and decrements of the main diagonal the matrix is tuned to obtain the minimum error in the flight trajectories, it is important to emphasize that this process is experimental.

From this experimentation it can be observed that the displacement in the Z axis (blue) does not present any impulse and in spite of the delay in reaching the desired position it remains almost stable during the whole trajectory, in the X axis (red) it can be observed that it has a impulse around 5% but it reaches its desired position quickly, the error in the Y axis (green) similar to that of the Z axis takes time to reach its desired position but in doing so it remains almost stable during the rest of the trajectory in Figure 11.

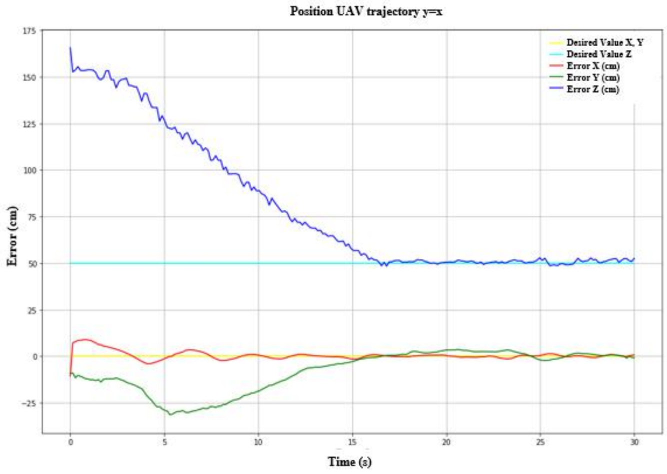


Figure 11. Errors in centimeters of the X, Y, Z axes of the UAV with inverse Jacobian calculation.

IV. RESULTS

The results obtained by comparing these two controllers are described below:

A. Position Errors on the X Axis

Considering as a reference the yellow line in Figure 12 you can see the errors in the X axis using a PID controller (blue line) compared with a controller calculating its Jacobian inverse (red line), you can see that the action time of the Jacobian controller is greater with respect to the PID, because the error decreases with greater speed, it is also appreciated that the error to stabilize is less than with the PID controller. The error obtained in the first case is 4% while in the second is 3% both on the scale of 100 cm, the setting time is 25 seconds and 10 seconds respectively.

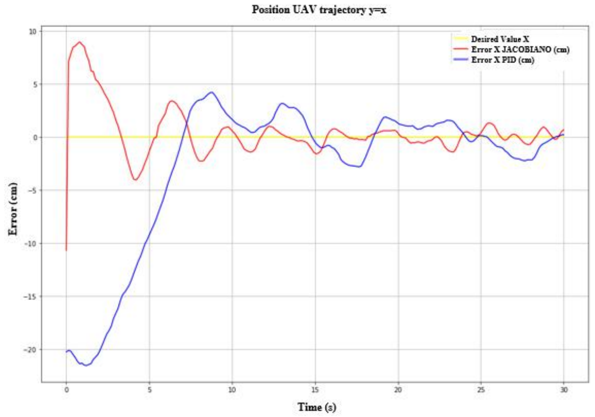


Figure 12. Comparison of errors in the X Axis by PID controller and Jacobian controller.

B. Position Errors on the Y Axis

Similarly considering as a reference the yellow line in Figure 13 you can see the errors in the Y axis using a PID controller (blue line color) compared with a controller calculating its Jacobiana inverse (red line color), where the PID controller presents a very large error in the first 15 seconds of testing, This is due to the fact that the UAV never reaches the height of the image in all its path, in comparison with the Jacobian controller it is appreciated that the error of positioning in the Y axis is smaller, although it never gets to stabilize because the image is in constant movement. The error obtained in the first case is in the range of 5% while in the second is 3% both on the scale of 100cm, the setting time is 25 seconds and 20 seconds respectively.

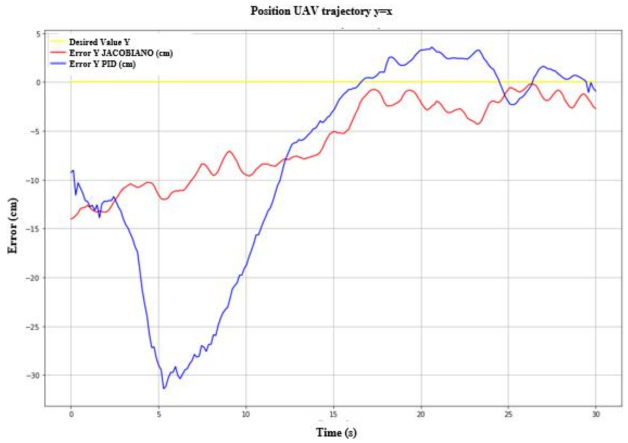


Figure 13. Comparison of Y-axis errors using PID controller and Jacobian controller.

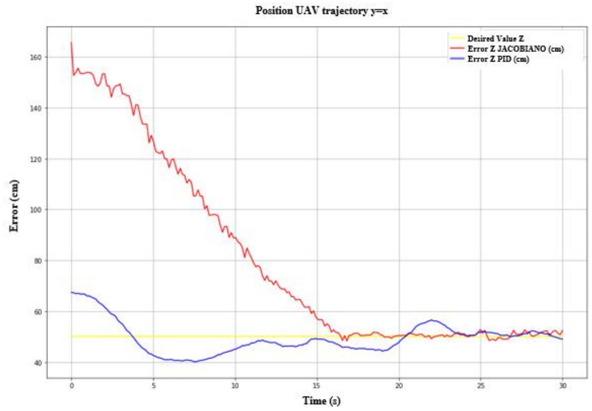


Figure 14. Comparison of errors in the Z axis by PID controller and Jacobian controller.

C. Position Errors on the Z Axis

Finally taking into account the yellow line reference in Figure 14 you can see the errors in the Z axis using a PID controller (blue line) compared to a controller calculating its Jacobin inverse (red line), when testing with the PID controller the positioning of the UAV acts faster with respect to the Jacobin control, On the other hand it can be seen how the error signal of the PID controller does not stabilize even though there is no movement of the pattern, on the contrary the Jacobin controller, despite the time it takes to position itself, stabilizes and has very small errors. The error obtained in the first case is in the range of 8% while in the second case it is 2% both in the 100 cm scale, the adjustment time will be 25 and 20 seconds respectively.

V. CONCLUSIONS

After the experiments and the data analysis it can be determined that a Jacobian type controller presents better characteristics than a classic PID controller, because the errors are lower than 5% in each of its axes in a scale of 100 cm for trajectories higher than 1 meter, even though the stabilization times are higher, additionally by the dynamics, the UAV can only rotate in the Z axis, that is, rotation in yaw with respect to the image. This means that all Y (pitch) and X (roll) rotation axes are eliminated for control purposes.

VI. FUTURE JOBS

As a complement to this study, the analysis of the communication speeds between the UAV and the computer is proposed in order to improve the efficiency of the controller. Additionally, this comparative study can be extended to the analysis of intelligent controllers.

ACKNOWLEDGEMENTS

We extend our thanks to Universidad de las Fuerzas Armadas ESPE for funding project 2018-207-ESPE-a-1 of which this article is a part. In addition to the research group Wicom Energy.

REFERENCES

[1] Getzin S., Nuske R., Wiegand K. "Using Unmanned Aerial Vehicles (UAV) to Quantify Spatial Gap Patterns in Forests" 2014, 6988-7004; doi:10.3390/rs6086988

[2] Amado X., “GPS in archeology: introduction and examples of use”. Proceedings of Archeology Laboratory and Cultural Forms (GIArPa), IIT, University of Santiago de Compostela, 1999.

[3] Chaumette F., Malis E., "2 1/2 D visual servoing: A possible solution to improve image-based and position-based visual servoings". Proceedings of the IEEE International Conference on Robotics and Automation (ICRA′00); San Francisco, CA, USA. 24–28 April 2000; pp. 630–635

[4] Thuilot B., Martinet P., Cordesses L., and Gallice J. "Position based visual servoing: Keeping the object in the field of vision". Proceedings of the IEEE International Conference on Robotics and Automation (ICRA ′02); Washington, DC, USA. 11–15 May 2002; pp. 1624–1629

[5] Raja M., Srivastava A., Dwivedi A., and Tiwari H. " Vision Based Tracking for Unmanned Aerial Vehicle" 2014, Advances in Aerospace Science and Applications. ISSN 2277-3223 Volume 4, Number 1 (2014), pp. 59-64

[6] Tao Dong, Liao X. H., Ran Zhang, Zhao Sun, and Song Y. D., "Path Tracking and Obstacles Avoidance of UAVs - Fuzzy Logic Approach" in 14th IEEE International Conference on Fuzzy Systems, 2005. FUZZ '05., Reno, NV, 2005, pp. 43-48

[7] Siebert S., Teizer J. "Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system" 2014, Elsevier

[8] Oh P. Y., Joyce M., Gallagher J., "Designing an aerial robot for hover-and-stare surveillance," ICAR '05. Proceedings., 12th International Conference on Advanced Robotics, 2005., Seattle, WA, 2005, pp. 303-308

[9] Koppány M., Busoniu L., “Vision and Control for UAVs: A Survey of General Methods andof Inexpensive Platforms for Infrastructure Inspection” 2015. Sensors (Basel, Switzerland). 15. 14887-916. 10.3390/s150714887

[10] Al-Kaff A., Qinggang Meng, Martín D., De la Escalera A., and Armingol J. M., "Monocular vision-based obstacle detection/avoidance for unmanned aerial vehicles" 2016 IEEE Intelligent Vehicles Symposium (IV), Gothenburg, 2016, pp. 92-97

[11] Shim D., Chung H., Sastry S., “Conflict-free navigation in unknown urban environments,” IEEE Robotics Automation Magazine, vol. 13, no. 3, pp. 27–33, Sept. 2006

[12] Shang E., An X., Li J., and He H., “A novel setup method of 3d LIDAR for negative obstacle detection in field environment” 2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC), Oct. 2014, pp. 1436–1441

[13] Ariyur K., Lommel P., Enns D., “Reactive inflight obstacle avoidance via radar feedback,” in American Control Conference, 2005. Proceedings of the 2005, June 2005, pp. 2978–2982 vol. 4

[14] Lin S., Garratt M., Lambert A, "Monocular vision-based real-time target recognition and tracking for autonomously landing an UAV in a cluttered shipboard environment" 2016, Springer Science+Business Media New York 2016

[15] Nex F., Remondino F., “UAV for 3D mapping applications: a review" in Società Italiana di Fotogrammetria e Topografia (SIFET) 2013, Springer

[16] Pestana J., Sanchez-Lopez J., Saripalli S., and Campoy P., "Computer Vision Based General Object Following for GPS-denied Multirotor Unmanned Vehicles" 2014 American Control Conference (ACC), June 4-6, 2014. Portland, Oregon, USA

[17] Monda M., Schaub H., “Hardware Simulation of Relative Navigation using Visual Sensor Information” AIAA Guidance, Navigation, and Control Conference and Exhibit 15 - 18 August 2005, San Francisco, California

[18] Vásquez M., Rodríguez H., “Seguimiento de una referencia visual en un plano con un cuatrirotor” 2015, Congreso Nacional de Control Automático, AMCA 2015, Cuernavaca, Morelos, México.

[19] Silva A., Peña C., Mendoza L., “Inspection and monitoring system using an aerial robot guided by artificial vision” 2013, ITECKNE, June 2005, pp. 190–198 vol. 10